Thermal Analysis of an RTV-655 Prototype Propellant Tank and a Test on the Use of Aerogel for Space Applications

Rishab Jain, CRESH student, Lausanne Collegiate School

Mentor: **Firouzeh Sabri**, Ph.D.

Department of Physics and Material Sciences, University of Memphis, Memphis, TN

***Abstract* – Space flight in the coming years will require advanced materials in order to combat the perennial problems of weight and insulation. RTV-655 is a rubber polymer with properties applicable for temperature resistance and its low density. In this experiment, RTV-655 is used as the material to construct a prototype fuel tank similar to those of modern space aircrafts. However, RTV-655 holds the advantage of being much lighter than current metal materials for tanks. After acquiring thermal data from the tank in a simulated liquid nitrogen test, it will be used as a baseline, and another tank will be constructed. This tank will be reinforced with aerogel, an ultra-light material with a low thermal conductivity, a practical material for use in space travel. After construction, this second tank will be tested for its thermal properties and compared to the first, helping to determine the feasibility of both RTV-655 and aerogel as a practical solution for space travel.**

***Index Terms* – RTV-655, aerogel, thermal conductivity**

I. Introduction

Though space exploration today is expanding, one of its weakest links the logistics of carrying fuel and keeping a light payload over longer periods. Modern propellant tanks use insulated metal to hold cryogenic fluids such as liquid hydrogen, helium and oxygen, but with such high-density metals, this creates a weight problem, requiring more fuel to propel a spacecraft. Along with that, the temperatures in space can vary from 20 K to 400K [1], subjecting these materials to large temperature differences and sometimes allowing the cryogenic propellants to self-pressurize. Such issues with cryogenic propellant storage and transfer are so critical that NASA has deemed them a high priority item for further development, the most important of which is a mission to Mars [2].

However, such problems can be solved with materials like polyimide aerogels, which have a low density, low thermal conductivity, and a very light weight, as some can be over 90% composed of air. [3] On the other hand, some aerogels can be somewhat fragile or brittle, and must be reinforced with other materials to operate effectively. This is where a material like RTV-655 steps in. RTV-655 serves as the main body of the prototype tanks in this experiment, offering a lighter alternative to dense metals.

To examine the effectiveness of polyimide aerogel in a prototype tank, two must be constructed, one with and one without aerogel, to compare results and figure out whether these materials can be considered space-grade.

II. Procedures

II A. RTV-655 Tank Testing

To establish baseline statistics for the aerogel/RTV combined prototype, a different tank was constructed out of only RTV-655 and put to a cryogenic test. In this instance, the "fuel" that this tank would hold would be liquid nitrogen, since it is easily accessible, safe, and simulates the cryogenic environment where liquid hydrogen and oxygen would be used in space.

The RTV-655 tank is placed in a closed chamber, where air cannot flow in or out to disrupt the testing process. The tank is rigged with thermocouples in four places: the top outside of the tank, the bottom outside of the tank, the top inside of the tank (known as the vapor thermocouple) and the bottom inside of the tank (known as the liquid thermocouple). Another thermometer lies outside of the tank but inside the chamber to measure the ambient temperature during the testing process. Supply valves and vent valves are also attached to keep a safe pressure and liquid amount inside of the tank.

Along with these thermocouples, the tank is hooked up to various extensometers. Though their data is not analyzed in this experiment, the diametral, axial, and circumferential extensometers measure the strain of the RTV-655 tank and how it holds up to the various stages to testing. Pressure sensors are also placed inside of the tank to measure throughout the tests.

The first stage of testing the RTV-655 tank is the precool stage. In this stage, both the liquid nitrogen supply valve and the tank vent valve are opened, allowing the liquid nitrogen to cool down the surroundings to cryogenic temperatures. It lasts anywhere from 100 to 150 minutes.

The second stage of testing is the pressurization stage. Like the name suggest, this stage is when the liquid nitrogen self-pressurizes. Both the vent valve and supply valve are kept closed, allowing nitrogen vapors to build up and expand the tank. Once the pressure difference between the inside and outside is more than 17 psi (known as 17 psig), a relief valve is opened to prevent the tank from bursting. This stage tests the strain of the RTV-655 in a short span, averaging just over 4 minutes.

The third stage is constant liquid, where the vent valve and supply valve are both kept open. This allows for a constant amount of liquid to remain in the tank, as the supply and venting keep the tank in relative equilibrium. This stage lasts 20 minutes.

The final testing stage is the boil-off stage. In this stage, the supply valve is closed and the vent valve is fully opened, exposing the liquid nitrogen to the outside of the tank and allowing it to boil out and complete the testing process. After all tests are completed and repeated accordingly, the data from the extensometers and thermocouples, as well as the pressure sensors can be extracted and analyzed.

Figure 1. RTV-655 test tank setup in controlled temperature chamber, with supply, vent, and relief valves, thermocouples, extensometers and pressure sensors.

II B. Aerogel Tank Construction

Aerogel can be embedded in a variety of ways, but with the resources available, it is easiest to use RTV to attach it to the tank. Mixing the RTV requires both RTV-655A, which is the substance of the polymer, and RTV-655B, which serves as the binding agent. 10 parts of the A liquid are mixed with 1 part of the B binding agent and thoroughly stirred to combine. At this point, some bubbles and foam appear in the mixture, and this may weaken the RTV-655 if left to cure at this point. To solve this, the mixture is placed in a vacuum chamber and outgassed, to ensure that the RTV-655 mixture is strong enough to cure. After outgassing and pouring into the tank mold, the RTV-655 is cured under a heat gun for a few days. The remainder of the RTV-655 is refrigerated to inhibit the curing process. After the tank body is completed, each small piece of aerogel is released from vacuum storage and placed onto the tank, with drops of RTV-655 laid on top and cured to tank body and with the heat gun. After laying an entire layer of aerogel, another layer of RTV-655 is added, along with one more layer of aerogel. The process is repeated for the other half of the tank and a layer of RTV is added in the middle to cure the two sides together. The tank is then ready for testing.

Figure 2. Aerogel tank under construction shown with heat gun and stabilization apparatus.

III. Results

III A. Temperature/Heat Transfer Analysis

A thermal analysis of the RTV-655 tank test results is necessary to ensure that the rubber polymer can hold up to varying temperature much like a space environment. To measure this, not only are temperature analyses necessary, but also a heat transfer analysis of various stages in testing. In this case, Fourier's Law is used to examine the conduction of the RTV-655. Shown below: [4]

$$q = -k\frac{dT}{dx}$$

Where:
- q represents heat flux
- k represents thermal conductivity
- t represents temperature
- x represents distance or thickness of material

In Figure 3, the precool graphs follow the predicted path: as liquid nitrogen is introduced into the tank, the temperature drops, and eventually reaches cryogenic levels after about 150 minutes. Figure 4 looks at the heat transfer of the constant liquid phase, which is a relatively straight line. This is because the constant liquid phase keeps the supply and vent valves both open, making the outside temperature cooler and keeping a constant heat transfer throughout the 20 minute stage. Figure 5 displays the heat flux for the boil off stage, which shows a flat line until around the 30 minute mark. There, the heat transfer drops as much of the liquid nitrogen begins to boil out of the tank. As the temperatures from outside and inside begin to even out, the temperature difference (as well as the heat flux) drops.

Figure 3. Temperature-Time graph of the precool phase, with each line represent each of the four different tests.

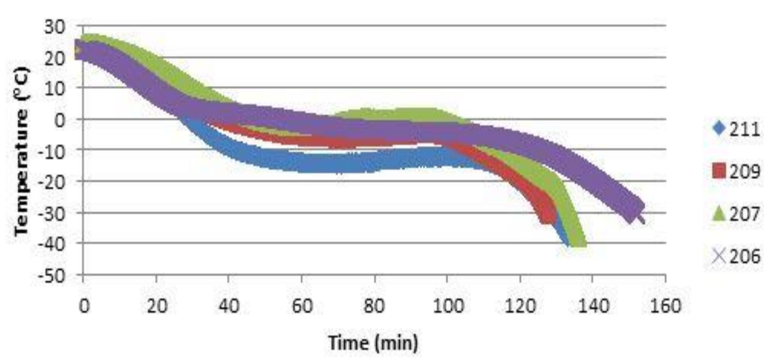


Figure 4. Heat Flux-Time graph for the constant liquid phase. The line is an average line from all four data sets from all four tests from the top outside and vapor thermocouples.

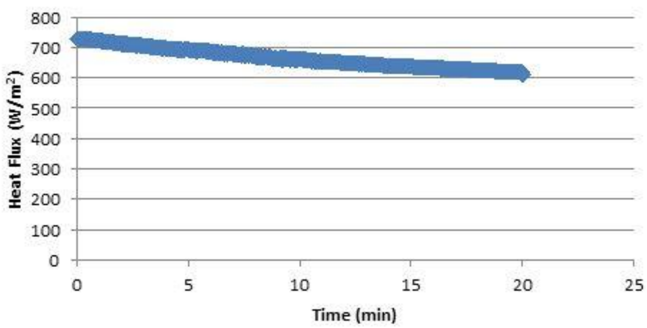
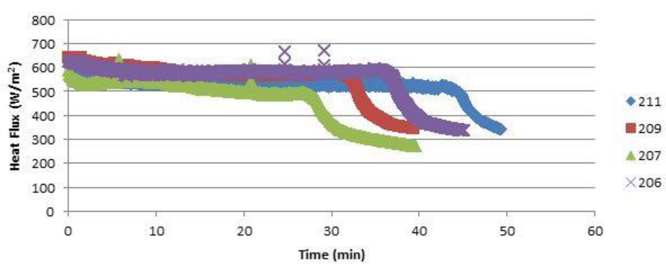


Figure 5. Heat Flux-Time graph for the boil off stage, with each line representing one of four different tests.

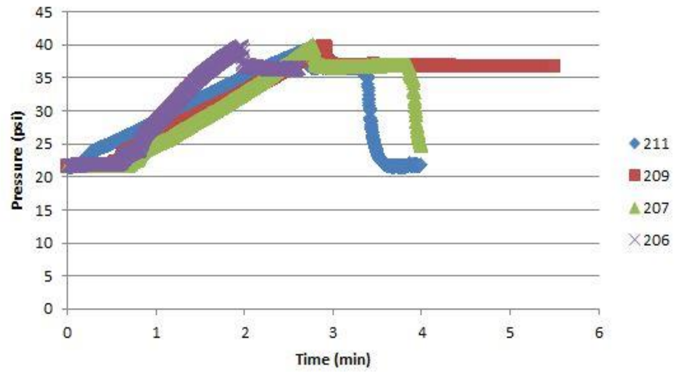


III B. Pressure Analysis

The main phase of analysis for pressure data is the pressurization phase. Because it tests the flexibility and pressure capacity of the RTV-655 tank, the pressurization phase is short but captures enough data to make conclusions regarding the feasibility of RTV-655 in space conditions.

All of the pressurization graphs follow a similar shape, with varying times. For the first 2-3 minutes, the pressure quickly climbs inside the tank. This is because the supply and vent valves are both closed, leaving the liquid nitrogen to quickly boil and pressurize the tank. At the end of this climb, a pressure relief valve pops open (at a pressure difference of 17 psi) to prevent the tank from bursting. This is seen in the small tick downward at approximately the 3 minute mark. After opening the release valve, the tank pressure remains constant until the end of the test. In some cases (such as test 211 and 207), the pressure quickly drops before the end of the test. This is because the main vent valve was opened earlier, in preparation for the constant liquid phase. However, the results from the pressurization phase show that RTV-655 as a tank material can withstand high pressures during pressurization, a key element of a space-qualified rubber in volatile space conditions.

Figure 6. Pressure-Time composite graph of the pressurization phase. The various colored lines are the test results from four different tests.



IV. Discussion and Conclusions

These results were used to test both the thermal and pressure properties of RTV-655, and re-confirm its use as a space-qualified rubber. The RTV-655 tank proved itself a reliable receptacle for cryogenic fluids in space, essential for fueling an extended spaceflight. However, more experimentation and analysis can always be added to such an experiment. For example, various air pressures were not simulated in the environment outside of the tank. Therefore, further testing regarding the vacuum of space surrounding the RTV-655 tank should be conducted [5]. Along with that, completion and similar testing should be done on the aerogel embedded tank. Though further proof is required, the likely predictions are that the properties of aerogel will help the RTV-655 tank in insulating cryogenic fluids and lowering overall heat transfer. Along with that, various tests could be done on how RTV-655 holds up to various high speeds, since the escape velocity and orbital velocity of the Earth are very high and could easily break apart some materials. Further experimentation must be done with these parameters in order to understand fully the properties of both RTV-655 and polyimide aerogels before their large scale use in space applications.

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References

[1] Pumroy, David. "Thermal Characterization of Polyimide Aerogels for Cryogenic Tank Applications." *American Institute of Aeronautics and Astronautics* (n.d.): n. pag. Web. 16 July 2015.

[2] Dunbar, Brian. "Aerogels: Thinner, Lighter, Stronger." *NASA Aeronautics*. NASA, 28 July 2011. Web. 13 July 2015.

[3] NASA. "Cryogenic Propellant Storage and Transfer Project." *NASAfacts*. National Aeronautics and Space Administration, Sept.-Oct. 2013. Web. 13 July 2015.

[4] Lienhard, John H. *A Heat Transfer Textbook*. Mineola, NY: Dover Publications, 2011. Print.

[5] Pumroy, David W., Douglas S. Williams, and William A. Parker. *American Institute of Aeronautics and Astronautics* (2015): n. pag. Web. 13 July 2015.